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Tendon Repair by Laser Welding: A Histologic and Biomechanical Comparison and Suture Repair With CO_2 and Argon Lasers

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Background and Objective: **The purpose of this study was to determine whether welding of tendinous tissue is possible with the application of thermal lasers.**
Study Design Materials and Methods: **After sharp transection of a unilateral achilles tendon, 40 male outbred Spraque Dawley rats were divided equally between four treatment groups. Ten animals underwent repair using the modified Kessler suture technique. The remaining animals underwent application of laser after the tendon edges were reapproximated and held in place with a vascular clamp. CO_2 and Nd:YAG lasers were applied using 25% human albumin as a solder. Fluorescein dye was added to albumin and used as solder for the Argon laser. Biomechanical and histologic testing were performed immediately and 14 days postoperatively.**
Results: **Argon and CO_2 lasers successfully fused the tendon ends together. However, immediately postoperative, the resultant tissue weld was tenuous and conventional tensile strength testing was not possible. At 14 days postoperatively, all modes of tendon repair resulted in tensile failure at consistently lower levels of tension than those required for the normal uninjured tendons. The ultimate tensile strength for the suture-repaired, CO_2 laser welded, and Argon laser welded tendons were 74%, 59%, and 64% of the strength of the control tendons respectively. No statistically significant difference was found in the tensile strength among the three repair groups. Histologic evaluation at 14 days revealed the greatest degree of inflammatory response in those tendons repaired with the Argon laser. Those tendons repaired with suture demonstrated the least amount of inflammatory change.**
Conclusion: **Our study demonstrates that welding of a tendon is possible with the application of laser energy. However, we were unable to produce a weld sufficient to withstand significant tensile loads in the immediate postoperative period.**

Key words: laser, tissue welding, tendon repair

INTRODUCTION

Thermal lasers have been used clinically to cut, coagulate, and ablate tissue with some success. The effect of laser energy depends upon the

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type of laser used, how that particular wavelength of energy affects the tissues upon which it is acting, and the amount of power that is placed on the tissue. As experience with lasers widened, researchers began to explore whether laser energy could be sufficiently controlled at low power to eliminate the zone of vaporization and produce only a zone of coagulation. Early work by Jain and Gorish [6] demonstrated successful sealing of arteriotomies and venotomies in a rat model. Subsequent investigators have shown that the CO_2 and Argon lasers could be used to make fast, watertight vascular anastomoses [2,3]. Poppas and Ganesan have shown improved results in welding vascular and urologic tissue when using adjuncts such as a protein solder [5,11]. More recently, Chuck and Wider have shown further improvements using chromophores to perform laser welding in a variety of tissues while minimizing collateral thermal damage [15,4].

Treatment of the ruptured or lacerated tendon has undergone several advancements, notably microsurgical suture techniques which increase precision of suture placement and lessen damage and inflammation caused by tissue manipulation [1]. The goal of tendon reconstruction is solid and permanent repair of the tendon that will glide normally through its surrounding tissues.

The object of our study was to determine whether welding of tendinous tissue is possible with the application of laser energy. We also attempted to determine whether some thermal laser wavelengths produce better tendinous attachments than others, as measured by tensile strength and histologic analysis.

MATERIALS AND METHODS

Tendo Achilles repair integrity was evaluated biomechanically and histologically in a series of 40 adult male Sprague-Dawley rats. The rats were divided into four injury management groups. Anesthesia was achieved by intraperitoneal pentobarbitol (6.25 mg/100 gm). All surgical procedures were performed under sterile conditions with the aid of an operating microscope (OpMi 1S, Zeiss, Germany). One 1.0 mm K-wire was inserted through the os calcis into the tibia, immobilizing the ankle in plantarflexion. A 3 cm midline incision was made over the achilles tendon and the tendon was isolated from the surrounding fascia. The tendon was sharply transected with a scalpel in its midsubstance, 0.5 cm from its calcaneal insertion.

In 10 of the animals (group I), immediate surgical repair of the transection was performed using the modified Kessler suture technique described by Kleinert et al. [7]. The sharply cut tendon ends were grasped centrally and repaired using a 7-0 ethilon monofilament nylon on a P-6 cutting needle (Ethicon Inc., N.J.). The wounds were irrigated with 1 cc of saline and the skin closed with 3-0 catgut suture. The wounds were sprayed with betadine paint and the animals recovered on a heating pad. No operation was performed on the opposite, uninjured hindlimb. The average time to complete the modified Kessler suture technique was 12 min.

Ten animals (group II) underwent immediate welding using a an unmodified Sharplan 10600 nm CO_2 laser. The power setting of the laser was maintained at 0.2 watts which calibrated to a real output of 0.34 watts. The cut tendon ends were reapproximated and held in place with a microvascular clamp. Twenty-five percent human albumin (Highland Laboratories, for Travenol Labs, CA) was used as solder. A 23 gauge needle on a 1 cc syringe was used to place the albumin directly into the field. The laser was applied from a distance of 2–3 cm until the tissue underwent a visual change in color and consistency, indicating coagulation. This change appeared as a tan discoloration of the tissue and a change in the consistency of the solder from liquid to gel. The helium-neon target spot of the laser was centered over the tendon edges and the CO_2 laser beam was swept over the field. The tendon ends were welded in a circumferential manner using the vascular clamp to invert the tendon. The vascular clamp was released, the wound was irrigated with 1 cc of saline, and the skin was closed using 3-0 catgut. The average time to complete the tissue weld was 4 min.

In 10 other of the injured animals (group III) the cut tendon ends were reapproximated and held in place with a microvascular clamp. The tendon ends were then welded together using an unmodified Coherent Innova 100 Argon laser. The power setting was maintained at .2 watts and was calibrated using a Coherent Labmaster E prior to each specimen welded. A 1:1 mixture of 10% fluorescein and 25% albumin was used as solder. The fluorescein was used as a chromophore in order to increase laser energy absorption. This solder was applied in a dropwise fashion to the center of the field. The argon laser was

applied with a hand held fiberoptic cable from a distance of 1–2 cm. The endpoint of welding was a visual change in the tissue. The wound was irrigated and closed with 3-0 catgut. The average time to accomplish tissue welding was 5 min.

The 10 remaining animals were to have undergone welding with an unmodified Nd:YAG 1640 nm laser. However, during the first several attempts at welding it became apparent that the laser, even at the lowest available power setting of 1 watt, would not facilitate a successful weld. The tendon edges retracted and the tissue desiccated with application of the laser. After multiple attempts at welding this treatment group was dropped from the study.

On the 14th postoperative day, the animals were anesthetized and the normal contralateral achilles tendon was lacerated and repaired with either CO_2 laser welding or Argon laser welding for the purpose of observing the immediate (time zero) effect of laser welding on the rat tendon. This was done in an effort to use fewer animals. After 90 min the animals were euthanized with intraperitoneal pentobarbitol (15 mg/100 ml).

Histologic and biomechanical testing were performed at time zero and 14 days postoperatively. At sacrifice, a visual assessment of the healed tendon was made and bilateral achilles tendons were resected, preserving the attachment to the calcaneus. The specimens were then randomly assigned to tensile strength testing (n = 6), histologic assessment (n = 3) or electron microscopic evaluation (n = 1). Six uninjured contralateral hindlimbs were chosen at random to serve as controls for tensile strength testing. Specimens randomized to tensile strength testing were immediately frozen to −80°C. Prior to testing the specimens were thawed to room temperature.

At time zero the measurement of tensile strength was not possible in those tendons treated with Argon and CO_2 lasers. The welded tissue ends separated during the harvesting of the tendon or during the manipulation prior to mounting the specimen on the Instron machine. Morphologic examination of this treatment group was performed.

The mechanical integrity of the 14 day postoperative specimens was studied in an Instron machine (model 1011, Instron Corp., Canton, MA). The proximal end of the achilles tendon was gripped securely in a custom manufactured serrated grip. The foot of the rat was secured distally in a pair of serrated Instron grips. Each specimen was loaded to failure at a constant Instron crosshead speed of 500 mm/min. All tendons ruptured mid-substance and tendon rupture was considered tendon failure. Load cell output versus displacement was recorded by a Series IX Automated Materials Testing System 6.02. The mechanical properties of each tendon were then calculated from these force/deformation curves. The mechanical parameters evaluated were ultimate tensile strength, elastic modulus (defined as the slope of the most linear region of the load deformation curve) and energy to failure.

Experimentally treated tendons randomized to morphologic analysis were fixed in buffered Formalin saline (pH 7.4), dehydrated and embedded in paraffin wax. Six micron coronal sections were cut, stained with hematoxylin and eosin, and examined in a blinded fashion.

RESULTS

Biomechanical Observations

Ultimate tensile strengths of the uninjured achilles tendons served as controls and demonstrated fairly consistent material properties. Ultimate tensile strength varied from 49 N to 32.5 N with a mean of 42.5 N and a group standard deviation of 5.5 N.

At time zero, the measurement of tensile strength was not possible due to the tenuous nature of the weld. The tendon ends separated during harvesting or during mounting of the specimen on the Instron machine.

At 14 days postoperatively all modes of tendon repair resulted in tensile failure at consistently lower levels of tension than those required for the normal uninjured tendons. The ultimate tensile strength for the suture-repaired, CO_2 laser welded, and Argon laser welded tendons were 74%, 59%, and 64% respectively. Using one-way analysis of variance, Kruskal-Wallis one-way AOV, and Tukey's pairwise comparison no statistically significant difference was found in the tensile strength among the three repair groups.

The mean elastic modulus of the control tendons was 17.8 N/m2 with a standard deviation of 1.5 N/m2. All of the experimentally treated tendons displayed lower values compared to the normals. The suture treated, CO_2 laser treated, and Argon laser treated tendons were 61%, 76%, and 48% as stiff as the normal controls.

The force deformation curves were digitalized and the energy to failure (the area under the curve) was calculated using Sigma Scan (Jan-

TABLE 1. Biomechanical Data From Controls, Suture Repaired, and Laser Welded Tendons*

Treatment	Ultimate Tensile strength (Newtons)	Stiffness (N/m2)	Energy to failure (Nm)
N1 control	42.5 (5.5)	17.8	1.6
Suture	31.5 (8.5)	10.9	1.1
CO_2 laser	25.0 (11.3)	13.5	0.8
Argon laser	27.1 (11.9)	8.5	1.0

*Standard deviations for each treatment group are in parentheses.

del Scientific, San Rafael, CA). The energy to failure of the normal controls was 1.6 Nm with a group standard deviation of 0.4 Nm. The experimentally treated tendons exhibited lower energies to failure than the controls. The energy to failure of the suture treated, CO_2 laser treated, and Argon laser treated were 69%, 50%, and 62% of the controls. The biomechanical observations are summarized in Table 1.

Histologic Observations

Histologic evaluation of each tendon was performed in a blinded fashion. All time zero specimens were accurately identified by the absence of inflammatory response. Evaluation of the suture repaired tendons at time zero revealed a small amount of edema in the muscle evidenced by separation of individual muscle cells. This edema outside the region of repair was present in all three tendons. Tendons repaired with a CO_2 laser revealed a small area of coagulation on the surface of the tendon edges. This coagulum was identified by its basophilic staining characteristics. In those tendons treated with an Argon laser there was a significantly larger coagulum that extended the entire width of the tendon ends. With this broader coagulum there was partial separation of the tendon ends in 2 of the 3 specimens. In both of the laser treated groups there was evidence of crush injury, away from the region of repair.

The tendons examined at 14 days were evaluated for separation of the tendon ends, the degree of inflammatory reactive change, and the amount and organization of the fibroproliferative repair. In the tendons repaired with suture there was a mild inflammatory response in the peritendinous tissues. The fibroproliferative response was mild to moderate and appeared reasonably well organized. None of the three tendons demonstrated a gap in the region of the repair. In those tendons treated with a CO_2 laser there was a moderate inflammatory response within the muscle and in the peritendinous region. Perivascular mononuclear cell inflammation was present, indicating a low grade chronic inflammatory response. Fibroproliferative response was graded as moderate with less organization. The tendons were in continuity in two of three specimens with a thin bridge of fibrous tissue seen in the third specimen. Those tendons treated with application of an Argon laser were judged as having the greatest degree of inflammation including intense changes at the muscle tendon junction. The fibroproliferative repair was graded as moderate while the organization of this repair was graded as poor. A small gap was seen in one of the three tendons.

DISCUSSION

Thermal lasers have been applied to a variety of tissues with varying degrees of success. One of the most extensively studied area is the vascular anastomosis. Vascular anastomoses are subject to known physiologic stresses and analysis of laser fusion in this model established the validity of laser welding. In addition to producing a weld stronger than conventional suture anastomoses, laser welded anastomoses have been shown to produce less inflammation, both acute and chronic [9].

The application of laser energy to fuse tendons could prove a useful tool in many reconstructive procedures. Tendons are unique in their structure and function. Tendons are composed of densely packed, highly organized collagen bundles able to withstand significant tensile loads while gliding through surrounding tissues. The goal of tendon reconstruction is a solid and permanent repair that will not hinder motion. Tendon welding has several potential advantages over conventional suture techniques. Suture material produces a foreign body inflammatory response which may inhibit natural healing and promote adhesions.

The exact mechanism by which laser energy influences tissue welding is not clear. There is growing evidence that supports the view that thermal remodeling of tissue proteins by the laser light occurs [11]. Recently, the process of albumin denaturing has been established as to temperature and rate [16]. The albumin was found to completely coagulate at 70°C. Investigators have demonstrated superior strength of rat urethral welds when the surface temperature remained at

a constant 70°C. In this study the laser was preset to weld at a constant surface temperature [8]. If tissue welding occurs as a result of protein denaturing and coagulation then simultaneous coagulation of native protein and solder is desired. Advancements in the area of solders are ongoing. Human albumin in a concentration of 40–45% has been shown to produce a superior weld [10]. Additionally, dye-enhanced solders have shown promise. The addition of a chromophore to the solder to selectively absorb laser light and thereby reduce the amount of peripheral thermal injury has been demonstrated [4].

There have been no published reports on the morphologic effect of laser welding on tendons. Morphologic analysis in our study differed from that previously reported in vascular anastomoses. We saw greater tissue injury and inflammatory response in laser treated tendons than in those treated with suture. The crush injury away from the site of repair is likely due to the vascular clamp used to hold the tendon ends in close proximity. The fibroproliferative response at the site of repair was greater and more disorganized in those tendons treated with laser welding. The greater inflammatory response is attributable to thermal injury caused by the lasers. We believe a significant amount of the thermal damage is due to equipment limitations. With continued refinement of laser technology, particularly temperature surface monitoring, laser energy will be able to be delivered with greater precision.

Our study demonstrates that welding of a tendon is possible with the application of laser energy. However, in this study we were unable to produce a weld sufficient to withstand significant tensile loads in the immediate postoperative period. After 14 days, we found no significant difference in tensile strengh, elastic modulus, or energy to failure between laser repaired and suture repaired tendons. We feel that laser welding in the lacerated rat achilles tendon is a good animal model and with further refinement of technology and technique laser welding will become a useful adjunct in reconstructive surgery.

REFERENCES

1. Acland RD, Trachtenberg L. The histopathology of small arteries following experimental microvascular anastomosis. Plast Reconstr Surg 1977; 59:868–875.
2. Ashworth EM, Dasling MC, Olson JF, Hoaglund WP, Arnold M, Glover JL, Dalsing MC. Large artery welding with a milliwatt CO_2 laser. Arch Surg 1987; 122:673–677.
3. Choma TJ, Poppas DP, Presberg HJ, Cundiff M, Schlossberg SM. CO_2 laser urethroplasty in the rabbit: A preclinical model. Lasers Surg Med 1992; 12:639–644.
4. Chuck RS, Oz MC, Deiohery TM, Joanson JP, Bass LS, Nowygrod R, Treat MR. Dye-enhanced laser tissue welding. Lasers Surg Med 1989; 9:471–477.
5. Ganesan GS, Poppas DP, Schlossberg SM, Devine Jr. CD. Urethral reconstruction using the CO_2 laser: A preliminary evaluation. J Urol 1989; 142:1139–1141.
6. Jain KK, Gorish W. Repair of small blood vessels with Nd-YAG laser: A preliminary report. Surgery 1979; 85: 884–888, 1970.
7. Kleinert M, Gropper TP, Van Beek A. Trauma of the hand. Curr Probl Surg 1978; 10:1–45.
8. Klioze S, Poppas D, Rovick C, Choma T, Schlossberg SM. Optimal temperature values for laser welding of rat urethral tissues: Time zero studies. Lasers Surg Med 1992; Supplement 4:77 (abstract 346).
9. Kopchok GE, White RA, White GH, Fusitani R, Vlasak J, Dykhorsky L, Grundfest WS. CO_2 and argon laser vascular welding: acute histologic and thermodynamic comparison. Lasers Surg Med 1988; 8:584–588.
10. Poppas DP, Choma TJ, Rooke CT, Klioze SD, Schlossberg SM. Preparation of Human Albumin Solder for Laser Tissue Welding. Lasers Surg Med 1993; 13:577–580.
11. Poppas DP, Schlossberg SM, Richmond IL, Gilbert DA, Devine Jr, CJ. Laser welding in urethral surgery: improved results with a protein solder. J Urol 1988; 139: 415–417.
12. Schober R, Ulrich F, Santer T. Laser-induced alteration of collagen substrate allows microsurgical tissue welding. Science 1986; 232:1421–1422.
13. White RA, Kopchok GH, Donayve C, Abergel RP, Lyons R, Klein SR, Dwyer RM, Vitto J. Comparison of laser welded and suture anastomosis. Arch Surg 1986; 121: 1133–1135.
14. White RA, White GH, Fujitani RM, Vlasak JW, Donayre CE, Kopchok GE, Peng SK. Initial human evaluation of argon laser-assisted vascular anastomoses. J Vasc Surg 1989; 9:542–547.
15. Wider TM, Libutti SK, Greenwald DP, Oz MC, Yager JS, Treat MR, Hugo NE. Skin closure with dye-enhanced laser welding and fibrinogen. Plast Reconstr Surg 1991; 88:1018–1024.
16. Yang Y, Welch J, Rylander III HG. Rate process parameters of albumin. Lasers Surg Med 1991; 11:188–190.